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Allocation in Life Cycle Inventory Analysis for Joint Production

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Abstract. Allocation in joint production is still one of the unresolved and often discussed methodological issues in Life Cycle Inventory Analysis. Using the many years of experience of management sciences, a new classification scheme is proposed. It is postulated that companies perform allocation in joint production in view of optimising the products' performance (economic and/ or environmental), which helps them to maximise their profits. Therefrom it is derived that value judgements and negotiations are inevitable. The proposed classification scheme differentiates between the number of decision-makers involved, and the type of markets for joint products. Several decision-makers have to find fair allocation factors for their commonly operated joint production, whereas individual decision-makers may choose allocation factors considering the (economic and/ or environmental) competitiveness of their joint products. Applied on the case of a small-scale gas-fuelled combined heat and power plant, the methodology proposed shows a strong dependency on the disutility function, i.e., private costs, environmental damage costs or a combination of the two.

Keywords: Allocation; combined heat and power plant; energy systems; environmental damage costs; environmental external costs; Joint production; Life Cycle Assessment; Life Cycle Inventory Analysis; management sciences; spark ignition engine

1 Introduction and Overview

A large number of methodological approaches have been published in the past for the allocation of environmental burdens of processes which contribute to more than one product system (multi-function processes). Schneider (1996) identified more than twenty different approaches for the analysis of waste treatment processes, of life cycles of resources (material cascades) and for (co-)product comparisons. Lindfors et al. (1995) describe and discuss seven different allocation methods for open-loop recycling which may lead to contradicting results. The choice of an allocation method may play a similarly important role like the choice of an adequate electricity supply mix or the weighting of different safeguard subjects. It is not astonishing that the problem of allocation is perceived as one of the still unresolved fundamental problems in LCA methodology (cf. Udo de Haes & de Snoo, 1996). In the mean time, the International Standard "Goal and Scope Definition and Life Cycle Inventory", ISO 14041 (Anonymous, 1998) has been approved, which includes a three step procedure that tries to reduce the differences mentioned above (see separate box).

The paper, based on a Ph.D.-thesis on Life Cycle Inventory methodology (Frischknecht, 1998a) and on a previously published German paper (Frischknecht, 1998b), starts from allocation approaches used in management sciences. It gives reasons why value judgements may be involved in allocation, especially in allocation of joint production[1]. In certain cases, which will be specified below, allocation keys need to be chosen that cannot be substantiated objectively. Because of this inevitable need for subjectiveness, and because subjective choices cannot be defended, choices of allocation keys for jointly produced products are not defensible. Furthermore, the position of "system enlargement" in the three step allocation procedure of ISO 14041 (in the following called "ISO 14041 procedure") is questioned. The paper contains a proposal for a classification of allocation situations and allocation methods appertaining to these situations. The new approach is illustrated with the help of a gas-fired combined heat and power (CHP) plant for small-scale district heating networks in Switzerland.

2 Objectives and Propositions

J.S. Mill is often mentioned as one of the first economists who raised the question of an adequate procedure to allocate (private) costs to two jointly produced goods (Mill, 1848:105). Criteria used today for the allocation of costs are for instance given in Horngren et al. (1991:460). They differentiate between the following criteria:

a) cause and effect,
b) benefits received,
c) fairness or equity, and
d) ability to bear.

Ad a) The criterion "cause and effect" relies on physical, chemical or biological causation. It may be applied for the analysis of combined production (see footnote 1) where the output of co-products can be varied independently such as an oil refinery producing oil products (light fuel oil, gasoline, bitumen, etc.). This criterion corresponds to the second step of the ISO 14041 procedure and is not applicable to joint production processes.

[*] Presentation and Introduction of this set of articles see Int. J. LCA **4** (3) 175-179 (1999)

[1] In *joint* production, the share of co-product outputs is fixed. In contrast to that, the share of outputs is independently variable in *combined* production.

Ad b) The criterion of "benefits received" is used to allocate common costs according to the individual profits achieved by spending these common costs. The costs of common marketing activities, for example, may be allocated to the respective goods according to their individual increase in turnover due to these common activities. The criterion may be applied in cases where no market determines the price (value) of goods (products and services). The allocation of this kind of common costs (and, similarly, environmental burdens) will not be elaborated further.

Ad c) A fair allocation of common costs is required when several decision-makers are involved in a joint production process. It implies that there is a problem of decision-making which includes negotiations in view of a commonly accepted and supported solution. This may be necessary for investments in a dam, for instance, that is used for electricity production, flood protection, drinking water supply and irrigation, and where several decision-makers and profiteers are concerned. In Life Cycle Assessment such a situation may occur in voluntary coalitions, e.g., in the waste treatment sector. Waste "producers" may look for companies that are interested in using the waste as a secondary raw material. The criterion "fairness or equity" is not provided by the ISO procedure. However, it plays an important role in the classification described below.

Ad d) The criterion "ability to bear" allocates costs according to the co-product's capacity to bear production costs. The gross sales value and the estimated net realisable value method are representatives of an operationalised concept relying on this criterion. They consider the competitiveness of jointly produced products and result in a price structure that is optimal for the company's profit maximisation. Also this criterion is used in this paper.

It is postulated that companies perform allocation in joint production in view of optimising the products' performance (economic and/ or environmental) which helps them to maximise their profits. Therefore the principle of competitiveness is interesting for allocation problems in joint production in LCA which also deals with product comparisons. Whether mere monetary parameters (disutility functions) are suitable or useful applying the criterion "ability to bear" in LCA allocation will be discussed and illustrated in Sections 4 to 6[2].

Companies often act in competitive markets. Therefore different views and opinions – for instance on allocation issues - are foreseeable, natural and admissible. Companies may be affected by a competitor's way to allocate (economic and/ or environmental) burdens to his joint products. However, as long as they do not participate in the joint production they cannot directly influence the way allocation is carried out. This leads to the following two propositions, on which the approaches presented in this paper rely:

- Joint product allocation is made in view of the competitiveness of the goods produced. Value judgements and negotiations are therefore inevitable.
- If economic *and* environmental aspects influence consumer choices, economic *and* environmental aspects should influence the determination of allocation factors for consumer goods as well.

3 Allocation Problems in Life Cycle Assessment

The various kinds of co-production in LCA (sometimes also called multi-functional production) may be classified according to different criteria. The following distinctive features for processes and their corresponding allocation methods may be used:

a) joint or combined production of goods,
b) simultaneous or successive production of goods,
c) one or several decision-maker(s) involved.

Ad a) The correlation between a deliberate change in the amount of goods co-produced and its effects (on direct emissions and requirements) may be used as a distinctive feature. In combined production situations, physical causalities may be identified and, by varying them independently, may be used for the determination of the co-products' allocation factors. This is by definition not possible for joint production processes.

Ad b) Co-products may be produced simultaneously or successively. The production of heat and electricity in a CHP plant, for instance, takes place nearly simultaneously. From a physical viewpoint, however, production is successive because heat utilization occurs after electricity production and therefore is a kind of "waste heat" recovery. Because the operator of a CHP plant is dependent on the utilization of both co-products (electricity and heat) due to economic reasons, and because electricity and heat cannot be stored, we nevertheless may speak of simultaneous and also of joint production.

In contrast, transports of different goods back and forth between production processes are clearly successive. But the transportation process as a whole is a co-production process. Waste recovery and recycling processes are in an intermediate position. They treat wastes of preceding product systems and simultaneously produce secondary raw materials for a successive product system. Waste recovery and recycling processes deliver jointly produced goods (waste "treatment" service and the products made out of recycled material).

Ad c) Co-production processes may either be operated by one individual company representing one decision-maker or by several decision-makers based on a voluntary co-operation. The latter requires competitive (environmental and/ or economic) advantages for all partners involved. In cases of conflicting interests solutions *satisfactory to all* are required because such coalitions are voluntary.

In the ISO procedure, the classification of allocation situations reflects the flexibility in the outputs of co-products (criterion a), 2nd step of the ISO 14041 procedure for combined production and 3rd step of the ISO 14041 procedure for joint production, respectively). The time aspect (criterion b), simultaneity or succession) is also an important distinctive feature in the ISO procedure (i.e., open-loop recycling versus allocation). Criterion c), the number of decision

[2] In LCA, the use of monetary allocation criteria is disputed (cf., for example, BOUSTEAD, 1994) although it is explicitly mentioned in the third step of the ISO 14041 procedure.

makers involved, is of major importance and may be decisive for the allocation procedure and/ or allocation parameter to be applied. It influences substantially the way allocation is carried out and shows that value judgements are involved in the allocation procedure. Although it is not addressed by the ISO 14041 standard, criterion c) will be used as the central distinctive feature in this paper (→ *Fig. 1*).

4 Disutility Functions in Joint Product Allocation

The aim of company activities is the delivery of goods in demand and the realization of an adequate profit in order to preserve the company's capital. Companies use disutility functions, which show the (financial) "damage" caused by their activities, in order to maximise their profits. The company's disutility is usually expressed in (private) costs. In the course of discussions about sustainable development, the focus is shifted from mere financial considerations to social and - especially relevant for this paper - to environmental issues. Growing environmental awareness in the product market leads to an increasing number of life cycle considerations about the environmental impacts of goods. The commonly used disutility function "private costs" may therefore be enlarged with information about environmental impacts.

Such changes in consumer behaviour may as well influence the way allocation is carried out in the case of joint production. It is sufficient for a mere economic optimisation to allocate private costs according to the co-products' ability to bear costs. Hence, the corresponding disutility function is private costs. But if environmental aspects are supposed to be included in the consumers' decisions (and the fact that LCA results are published and paid attention to, supports this point of view), the disutility function should be enlarged accordingly. If purchase decisions are not based on private costs alone but include information about the environmental performance of competing goods, a company should perform joint product allocation taking private costs *and* environmental impacts into account in some way or another.

That is why the joint product allocation problem treated in this paper deals with the determination of

a) private costs,
   and
b) environmental impacts (e.g., expressed by one dimensional parameters such as environmental damage costs[3])

of jointly produced goods with the help of appropriate allocation factors in such a way that all co-products have a combined environmental and economic edge over competing goods.

Such an allocation may be carried out for costs and environmental impacts separately or together, by using an appropriate aggregation of the two dimensions of "economy" and "environment". With the approach described below, competitive trade in market societies is maintained, i.e. companies still strive for maximising profits. But it is assumed that they take environmental aspects into account in a systematic way. The economic disutility function used for profit maximisation is therefore enlarged with environmental information[4].

In the following, economic and environmental aspects are first considered separately and then jointly. To this purpose, environmental impacts are converted to monetary units and aggregated with private costs to so-called "social" costs.

The assessment of environmental impacts is made with Eco-indicator 95^{rf} which is based on the structure of the Eco-indicator 95 (GOEDKOOP, 1995)[5]. The relative weighting of pollutants of Eco-indicator 95 is compared to that of the ExternE studies (European Commission, 1995a-f; KREWITT et al., 1997; EYRE et al., 1997). Large discrepancies, in particular encountered for pollutants causing winter smog, summer smog, and global warming but also for heavy metals, are adjusted by changing characterisation and/ or reduction factors in the Eco-indicator 95 method. In addition to these changes, a new category "radioactive releases" has been introduced, which is also based on ExternE work (European Commission, 1995e). Three weighting factors (reduction factors) for global warming have been introduced corresponding to low, medium and high environmental damage costs due to climate change because the assessment of damage costs for global warming impacts is highly uncertain. Major influencing factors are the way damages in the far future are considered, the way human life is monetarised, and the climate sensitivity of our planet earth (cf. EYRE, et al., 1997).

Eco-indicator 95^{rf} points are converted to monetary units with the help of a top-down calculation. This is done under the assumption that today's and future environmental damage costs caused by today's European yearly emissions amount to 10% of today's European gross national product.

The important environmental impacts of energy systems assessed with the Eco-indicator 95^{rf} based on the low climate change damage costs scenario are particulates, sulphur dioxide and nitrogen oxides (both contributing to the creation of secondary particulate) but also radionuclides. Greenhouse gases are the decisive pollutants for the high climate change damage costs scenario.

5 Decision Tree for Allocation Problems in Joint Production

From the last two sections we learn that for co-production (or multi-functional processes) two main distinctive features exist on two distinct levels:

- The distinction between joint and combined production, and
- the number of decision-makers involved in an allocation procedure.

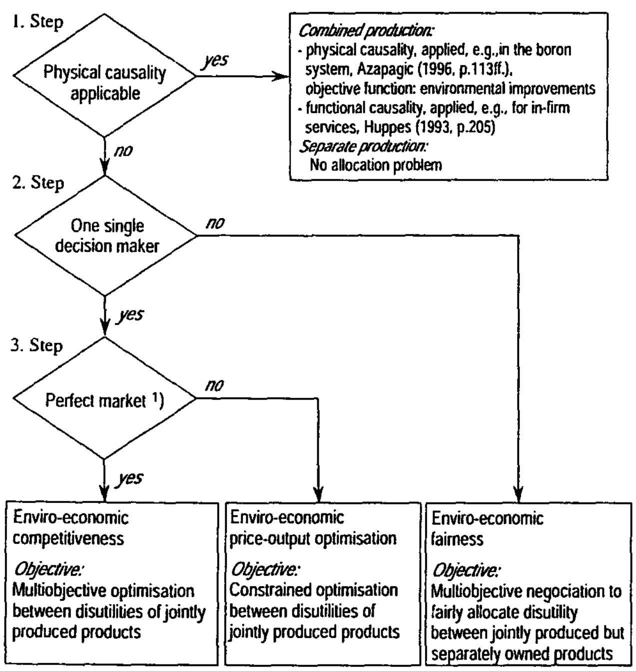
In combined production, physical causal relationships may be used to identify adequate allocation factors, something which is impossible in joint production. Individual decision-

[3] As determined for instance in the ExternE projects (European Commission, 1995a-f).

[4] The author is aware that such an aggregation is problematic and discussed controversially. Nevertheless, this approach is chosen to better highlight inherent value judgements needed in allocation.

[5] The impact assessment method Eco-indicator 95^{rf} is described in Frischknecht (1998a). The index "rf" indicates that the author (rf = Rolf Frischknecht) is fully responsible for the content of the assessment method.

makers may solve their allocation problem in line with their objectives, whereas a group of distinct decision-makers needs to pay regards for each other. Finally, individual decision-makers may operate in competitive or monopolistic markets which again influences their behaviour in allocation issues. This leads to the following decision tree for allocation problems in joint production (→ *Fig. 1*):



1): Perfect in the sense that the firms are price-takers, but *not* in the sense that environmental external costs have already been internalised completely.

Fig.1: Decision tree for allocation approaches in joint product allocation.

First the question arises whether physical causalities may be established, i.e., whether the process is combined or joint. For combined production the method of linear programming may be applied as has been shown by Azapagic (1996) for the production of boron products. Production may be optimised in terms of lowering production costs, maximising revenues (e.g., at equal production costs) or in terms of a reduction of air and water emissions.

In a second step, the number of distinct decision-makers taking part in a joint production process is evaluated. One individual decision-maker (a single company or a single division within a group), responsible for the joint production process and the sales of his or her products, is free in the choice of the allocation procedure and of allocation factors. His or her decision depends on the market situation under which the joint products are sold (third step). Product prices may be influenced either by means of a variation in sales volumes (in imperfect, monopolistic or oligopolistic markets) or they may be fixed as is the case in fairly well working markets.

Let us first have a closer look to the single decision-maker situation.

5.1 Competitive allocation made by one individual decision-maker

In imperfect markets, profits may be maximised by varying the output rate (enviro-economic price-output optimisation in *Fig. 1*). Demand functions (showing the relation between output and achievable product prices) are therefore required for all joint products. LCA results may be used to determine the optimum in terms of private costs *and* environmental impacts which can differ from the optimum in terms of private costs only. This case is not elaborated on here.

In perfect markets (enviro-economic competitiveness in *Fig. 1*), allocation factors may be determined according to the market situation (i.e., prices *and* environmental performance of competitors' products). Hence, the company operating a joint production process depends on the corresponding information of competing products. Having access to this information the performance of a production process delivering two joint products, for instance, may be optimised in terms of two eventually diverging objectives (→ *Fig. 2* and case study in Section 6). The fictive example in **Fig. 2** shows the disutility

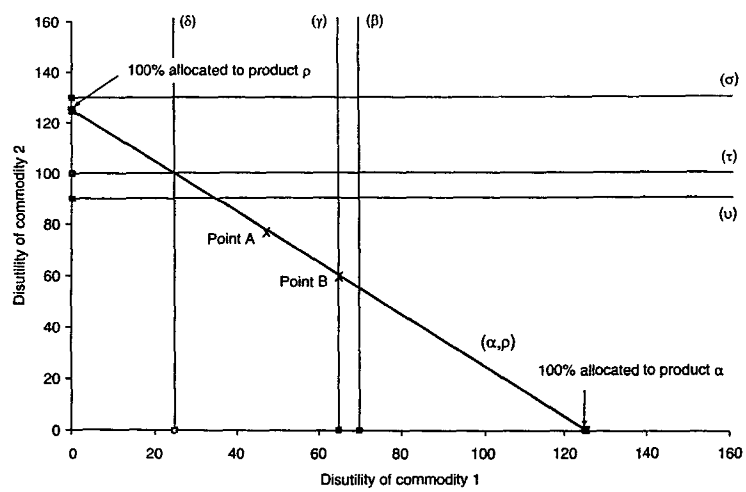


Fig. 2: Graphical solution for a comparison of the life-cycle based disutility of alternative combinations of commodities 1 and 2. The thick line shows the disutility of the joint products α and ρ. The points on the abscissa and the ordinate show the disutility of products from single output processes β, γ, δ,? and σ, τ, υ, respectively. Intersections of the vertical and horizontal auxiliary lines above the thick line show combinations of single-output processes with a higher disutility than that of the joint products α and ρ. In this paper, disutility is expressed by private costs, environmental impacts and a combination of the two ("social" costs). The scales show arbitrary units.

of brands of two commodities. There is one multi-functional (or joint) process, which produces the brands α,ρ. Furthermore three single output processes deliver the brands β, γ, and δ (of commodity 1) and σ, τ and υ (of commodity 2), respectively. The figure shows that, e.g., the combination δ,υ will in any case produce at a lower disutility than the joint production α,ρ. Points A and B show situations where the disutility of the jointly produced product ρ (commodity 2) is always lower than the disutility of product υ. But the disutility of α is always above the disutility of δ. Hence, no allocation factors exist where both α and ρ show a lower disutility compared to competing products δ and υ respectively.

The combination δ,τ is of equal rank compared to the jointly produced products α and ρ. Point B shows a situation where product α shows an equal disutility compared to product γ, but a lower disutility of ρ compared to υ.

Such graphs are therefore useful for the identification of ranges for allocation factors within which both joint products show a better or an equal performance than alternative combinations of single-output products. In Section 6, this approach will be illustrated with the example of combined heat and power production.

We will turn now to the situation where several distinct decision-makers are involved in the allocation procedure.

5.2 Fair allocation in voluntary coalitions

When several companies or divisions of a group participate in a joint production process (enviro-economic fairness in *Fig. 1*), an allocation procedure and allocation factors acceptable for all of them are required. Such negotiations, required for example in the field of emissions not (yet) traded on the market, can be modelled with game theory (cf. SHAPLEY, 1953; MÜLLER-FÜRSTENBERGER, 1998)[6]. A set of elementary rules ensures that

- no coalition partner is charged more than his or her stand-alone private costs (or environmental impacts or "social" costs). Its rationale is evident because the coalitions are voluntary (*"stand alone cost test"*).
- no coalition partner will be charged less than the marginal private costs (or environmental impacts or "social" costs) he or she will cause by being included in the coalition. Otherwise a partner would be subsidised by the rest of the coalition (*"incremental cost test"*).

The Shapley approach adds another condition to these two (SHAPLEY, 1953). The order in which a partner joins the coalition does not influence the share or profits received. This implies that all benefits are partitioned equally among the coalition partners.

The application of these rules narrows down the solution space, which otherwise, i.e., in situations with one independent decision-maker is theoretically unlimited. A simple example of a three party coalition is used to illustrate how this approach may be applied in LCA.

[6] Van Engelenburg & Nieuwlaar (1994) introduced a similar "allocation game" in LCA without explicitly referring to game theory.

Table 1: Disutilities and least incremental disutilities (measured in arbitrary units) for the production of products α, β, and γ in various

Coalition	Disutlity	Least incremental disutility			
	[-]	(α,β)	(α,γ)	(β,γ)	(α,β,γ)
ø	0	-	-	-	-
(α)	80	75	70	-	55
(β)	70	65	-	40	25
(γ)	150	-	140	120	100
(α,β)	145	-	-	-	95
(α,γ)	220				175
(β,γ)	190				165
(α,β,γ)	245				

The three firms, let us call them F_A, F_B, and F_C, are negotiating about possible coalitions to reduce the disutilities of their respective products α, β, and γ. **Table 1** shows the disutilities and the least incremental disutilities for all possible coalitions in arbitrary units.

The core of the disutility function is the set of all allocations for which the two conditions mentioned above are met. It may be solved either graphically or numerically. The maximum disutility allocateable to one single firm is the disutility of the grand coalition {α, β, γ}, namely 245 (→ *Table 1* and *Fig. 3*). The disutility for stand-alone production of product α are 80 and the lowest incremental disutility is 55. Hence, firm F_A would enter a coalition with either of the two or both partners if the disutility remains in between 55 and 80. For product β from firm F_B the corresponding limits are 25 and 70, respectively, and for product γ of firm F_C 100 and 150, respectively.

The core in this example is rather small so that the room for negotiations is restricted. The benefits minimally or maximally allocateable to each of the products lie within the core for all products. Hence, the reductions achievable may reach 31% for product α of firm F_A, 64% for product β of firm F_B, and 33% for product γ of firm F_C. Including the additional property of the Shapley approach, which states that benefits should be allocated equally among the coalition partners, the result of allocated disutility is 69.2 for product α, 49.2 for product β, and 126.6 for product γ. Compared to the stand-alone alternatives, firm F_B profits most by the coalition. It may reduce its disutility by nearly 30%, compared to some 14% for firm F_A and about 16% for firm F_C.

We may recognise a similarity to the "system expansion" approach or "avoided burden" approach, proposed in the ISO standard 14041. The "democratic" approach also uses information from "outside the system", from alternative systems delivering additional function(s) separately. However, not the *total* amount of environmental impacts avoided by joint production is allocated to one individual joint product. The environmental impacts "escaped" are rather allocated *evenly* or *fairly* among the coalition partners. With the "democratic" approach applied in a two parties coali-

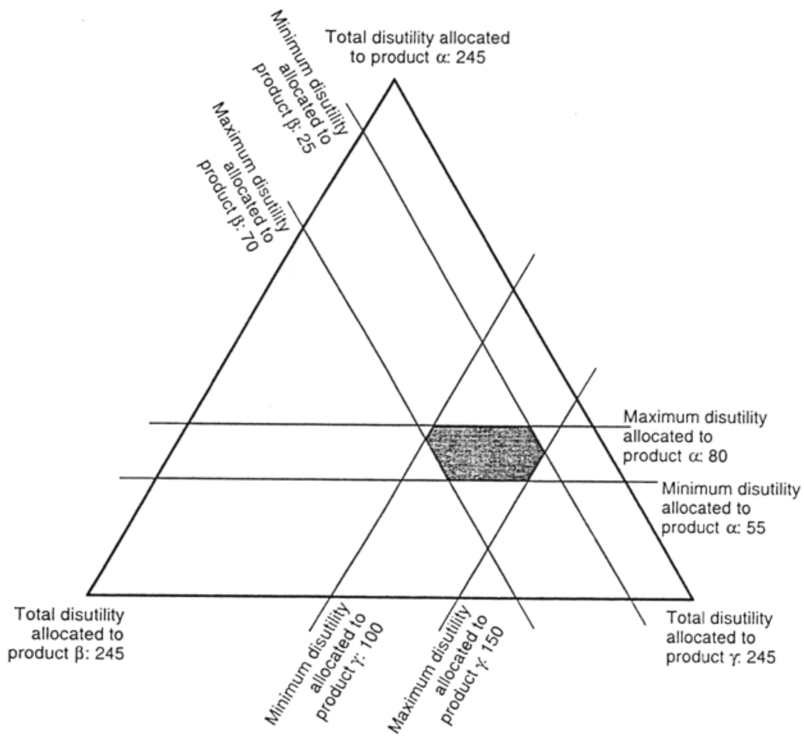


Fig. 3: The core (shaded) of the disutility function (in arbitrary units) for the coalition of firms F_A, F_B, and F_C to jointly produce products α, β, and γ respectively.

tion we therefore come close to the time-honoured fifty-fifty rule proposed in the "Technical Framework for Life-Cycle Assessment" published by SETAC in 1991, where it is suggested to "*equally divide impacts added to the system because of recycling. The inputs and outputs associated with recycling are: reduced disposal of Product 1, reduced virgin material production for Product 2, inputs and outputs associated with recycling, and any converting net inputs and outputs incurred as a result of using recycled materials over virgin materials in product 2*" (FAVA et al., 1991, p. 80).

It becomes also obvious that the "system expansion"- or "avoided burden"-approach determines one of the borders. The burdens of an alternative, single-output process solution of one coalition partner are subtracted from the burdens of the whole coalition of, e.g., two partners. The difference shows the minimum burdens to be attributed to the *second* partner (according to the "*incremental cost test*"). Allocating on the basis of this difference, the *first* partner will not profit at all because there is no difference in burdens between the stand alone option (alternative single-output process) and a coalition. Similar considerations may be made when the burdens of an alternative single-output process of the *second* coalition partner are subtracted from the burdens of the coalition. In this case the *second* partner would not profit from the coalition. That is why the "system expansion" – or "avoided burden" – approach will most probably be applied only in a context where *one individual* decision-maker can determine his or her allocation factors independently.

6 Competitive Allocation in Combined Heat and Power Production

A case study in the energy sector is used to illustrate the allocation procedure introduced for perfect markets[7]. The energy system analysed is a gas-fired combined heat and power plant with a thermal capacity of 360kW and an internal electric heat pump for upgrading waste heat from the spark-ignition engine. Two oil-fired boilers are used to cover peak load periods. They provide about 40% of the yearly heat requirement for the district heating network. Frischknecht (1998a) contains a detailed derivation of the results.

But is a combined heat and power plant a joint production process? Chemical properties are not applicable in this case because the goods (electricity and heat) stem from one main single input, namely natural gas. Physical causalities are more disputable. One might argue that electricity is always produced while it is physically not imperative to make also and always use of the waste heat. However, the same line of reasoning is also applicable in the opposite direction. One might only make use of the heat produced in a spark ignition engine and dissipate the mechanical energy co-produced. Although both considerations are theoretically right, they fail because they are economically inefficient. Power plants only generating electricity and boilers only generating heat are able to produce at less costs than the multi-functional CHP plant that would only be operated either for its heat or electricity

[7] Although a perfect market situation does not (yet) exist for electricity and natural gas in Switzerland.

generation. CHP plants are built to *jointly* produce electricity *and* heat which renders them economically competitive.

Furthermore, it must be emphasized that neither the energy nor the exergy content of the outputs influence the emission characteristics of a CHP-plant. That is why no parameters exist which reflect physical causalities (the requirement for parameters to be used in the second step of the ISO 14041 procedure) and by that would allocate emissions and requirements of the CHP plant in a non-arbitrary way. Therefore we need to move to the third step, namely the identification of other kinds of causalities or relationships. And here, arbitrary physical parameters such as energy or exergy, or economic parameters may be applied.

Energy content, exergy content, price, "motivation heat"[8], and "motivation electricity"[9] are used as examples of possible, arbitrary allocation parameters for determining the allocation factors shown in Table 2. Other allocation parameters resulting in different factors may of course be used. Even factors below zero and above one are possible and sometimes also sensible (see further below).

Table 2: Allocation parameters and allocation factors used in this paper for the gas-fuelled spark-ignition engine

No. in Figures 4 to7	Allocation Parameter	Allocation factors for	
		Heat	Mechanical energy
1	Energy	0.64	0.36
2	Exergy	0.25	0.75
3	Price	0.38	0.62
4	"Motivation electricity"	0	1
5	"Motivation heat"	1	0

[8] 100% of expenses and emissions of the gas-fuelled spark-ignition engine are attributed to the heat produced.

[9] 100% of expenses and emissions of the engine are attributed to the mechanical energy produced.

In a first step, private costs (investment and operating costs) of the CHP plant will be compared with other electricity and heat producing systems (→ *Fig. 4*). For pure heating systems (points on the ordinate, horizontal auxiliary lines), fossil-fuelled boilers show a clear advantage. Oil and gas boilers produce heat for similar costs of about 0.06 CHF per kWh, whereas wood chip boilers show twice these costs.

The specific costs of electricity producing technologies (points on the abscissa, vertical auxiliary lines) lie between 0.15 and 0.2 CHF per kWh_e (incl. transport and distribution), and the average redelivery tariff (the price paid by utilities for electricity fed into their grid) for CHP plants is about 0.12 CHF per kWh_e. The costs of 1kWh electricity saved by substituting an energy saving for an incandescent bulb are only about 0.02 CHF.

Costs for heat and electricity from the CHP plant are interdependent. The costs for heat amount to nearly 0.09 CHF per kWh_{th} if all costs are allocated to the heat produced (point 5 in *Fig. 4*). If all costs are allocated to electricity, electricity and heat show specific costs of about 0.25 CHF per kWh_e and 0.03 CHF per kWh_{th}, respectively (point 4). Costs for useful heat are not zero in this case because a part of the electricity produced is used to convert low temperature waste heat into useful heat with the help of an internal electric heat pump.

Fig. 4 can be used for an evaluation of combinations of technologies that show lower, equal and higher private costs compared to the CHP plant option. The case study shows for example, that heat and electricity produced in a CHP plant costs about as much as a combination of heat produced in a light fuel oil boiler and electricity produced in a run of river power plant (Point A in *Fig. 4*).

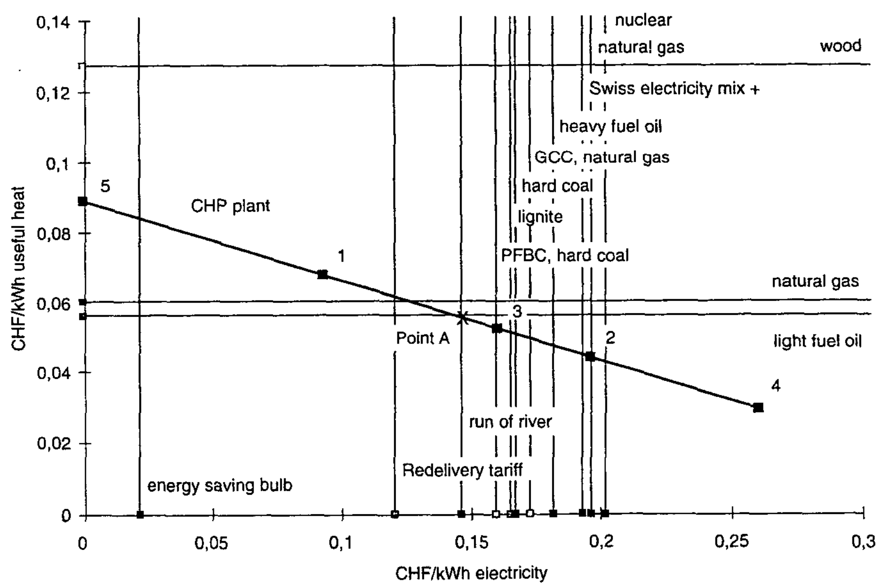


Fig. 4: Life-cycle based private costs for the production of useful heat and electricity with different, average and new technologies. CHP: Combined heat and power plant with oil-fired peak load boilers; PFBC: hard coal-fired pressurised fluidized bed combustion; GCC: gas-fired gas combined cycle. Redelivery tariff: Price paid by utilities for electricity fed into their grid. CHF: Swiss Francs (1 CHF = 0.63 Euro)
Allocation parameters: 1: Energy, 2: Exergy, 3: Price, 4: "Motivation electricity", 5: "Motivation heat"

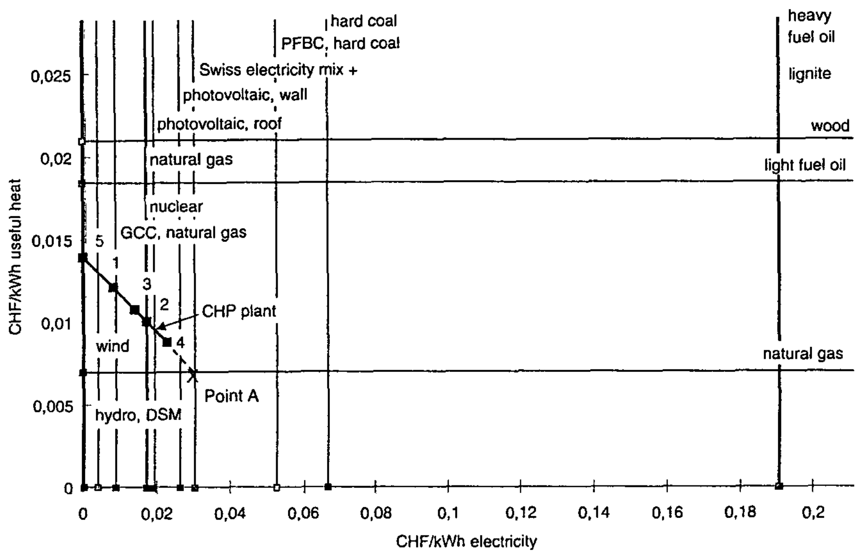


Fig. 5: Specific life-cycle based environmental damage costs for the production of useful heat and electricity with different average and new technologies including low damage costs for climate change (CHF 4.20/t CO_2). CHP: Combined heat and power plant with oil-fired peak load boilers; PFBC: hard coal-fired pressurised fluidized bed combustion; GCC: gas-fired gas combined cycle. DSM: Demand side management (energy saving instead of incandescent bulb).
Allocation parameters: 1: Energy, 2: Exergy, 3: Price, 4: "Motivation electricity", 5: "Motivation heat"

Similar considerations can be made on the level of environmental impacts. Fig. 5 and 6 show the environmental impacts of the same technologies shown in Fig. 4, expressed this time in environmental damage costs per kWh. Because of particularly high uncertainties in determining environmental damage costs of global warming (see Section 4), two different scenario (low and high) are shown. The two scenario are derived from data published in Eyre et al. (1997). Large differences between different technologies but also between electricity and heat become obvious.

In the low CO_2-damage cost scenario (→ *Fig. 5*), existing fossil-fuelled power plants only partially equiped with flue gas treatment (heavy fuel oil: average Italian fuel oil power plant, lignite: average German lignite power plant) cause by far the largest amount of environmental damage costs of all the power plants shown here. Even if the total amount of environmental damage costs of the CHP plant are allocated to electricity (point 4) its specific damage costs are far below the ones of the power plants mentioned. But even if all environmental damage costs are allocated to electricity, gas-fired condensing boilers can

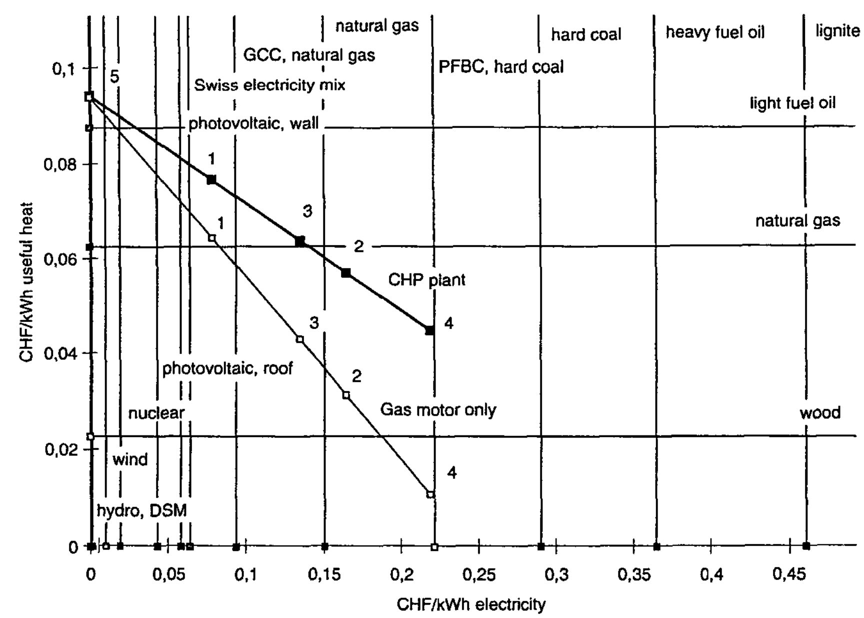


Fig. 6: Specific life-cycle based environmental damage costs for the production of useful heat and electricity with different average and new technologies including high damage costs for climate change (CHF 210/t CO_2). CHP: Combined heat and power plant with oil-fired peak load boilers; PFBC: hard coal-fired pressurised fluidized bed combustion; GCC: gas-fired gas combined cycle. DSM: Demand side management (energy saving instead of incandescent bulb). Gas motor only: Only spark-ignition engine (excluding oil-fired peak load boilers).
Allocation parameters: 1: Energy, 2: Exergy, 3: Price, 4: "Motivation electricity", 5: "Motivation heat"

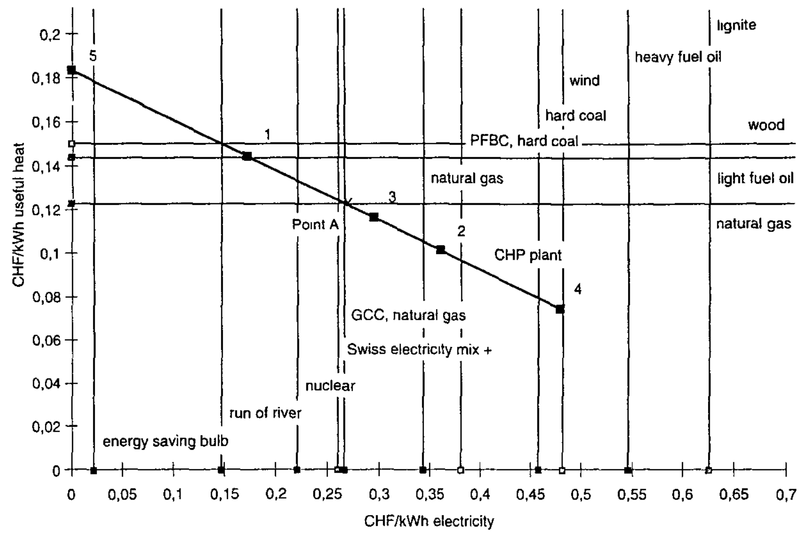


Fig. 7: Specific life-cycle based "social" costs for the production of useful heat and electricity with different average and new technologies including high damage costs for climate change (CHF 210/t CO_2). CHP: Combined heat and power plant with oil-fired peak load boilers; PFBC: hard coal-fired pressurised fluidized bed combustion; GCC: gas-fired gas combined cycle.
Allocation parameters: 1: Energy, 2: Exergy, 3: Price, 4: "Motivation electricity", 5: "Motivation heat"

produce useful heat at lower environmental damage costs. At Point A in Fig. 5, the environmental damage costs of heat from the CHP plant equal the ones of the condensing gas boiler. At this point, the allocation factor for electricity is *above one* and the allocation factor for useful heat is *negative*.

Point A corresponds to an "avoided burden" approach for a CHP plant, where all environmental impacts are allocated to electricity and the environmental impacts of a condensing gas boiler are subtracted. This shows, that the "avoided burden" approach (one way of system expansion) is just a special case of an allocation factor when using one-dimensional indicators (disutility functions). In this respect the ranking order of the ISO 14041 procedure is questioned, which puts "system expansion" in step 1, economic and other relationships, however, in step 3.

In the high CO_2-damage cost scenario (→ *Fig. 6*), fossil-fired power plants are grouped closer together. Technologies based on renewable and carbon-free energy sources (hydro power, wind power, photovoltaics, wood and nuclear power) show advantages in comparison to the gas-fired CHP plant. For example, the specific environmental damage costs for CHP useful heat and electricity are always higher than the costs for wind power and useful heat from wood boilers whatever allocation factor is chosen.

As explained in Section 4, environmental aspects may play a role in joint product allocation *in addition* to economic aspects. Under the premise that clients of joint products will make their decisions based on economic *and* environmental considerations, it may be useful to combine costs and environmental impacts. Such a combined enviro-economic parameter may then be used as a more appropriate disutility function to determine allocation factors optimal for a company whose clients care for environmental issues. Fig. 7 shows such a situation in which private costs and environmental damage costs are aggregated on a one to one basis[10] to so-called "social" costs.

Compared to an individual solution where heat is provided with a condensing gas-fired boiler and electricity is produced in a modern coal power plant (PFBC[11]), the CHP plant shows advantages for both heat and electricity when using allocation factors for electricity between 0.55 and 0.75 (which is located between points 3 and 2 in *Fig. 7*). Within these limits "social" costs of useful heat and electricity produced in the CHP plant are lower than the "social" costs of useful heat from a gas boiler and coal electricity. A gas-fired GCC power plant instead of the coal power plant will reduce the range of favourable allocation factors to one single point (Point A in *Fig. 7*, allocation factor electricity about 0.55).

The "social" costs of useful heat and electricity from gas boilers and nuclear power plant, respectively are below the "social" costs of the CHP plant option. No allocation factors exist where both heat and electricity from a CHP plant show lower "social" costs. The option "CHP plant (with oil-fired peak load boilers)" is therefore less "efficient" than the combination of useful heat and electricity from gas boilers and nuclear power plant, respectively.

7 Conclusions

Starting from management sciences the problem of joint product allocation has been further developed for its use in Life Cycle Assessment.

It has been shown on a theoretical basis that the context in which an allocation problem occurs is an important and

[10] The exchange rate between environmental damage costs and private costs equals 1, i.e. 1 CHF environmental damage costs equal 1 CHF private costs. Other exchange rates may be chosen according to the uncertainty perception of the decision maker.

[11] PFBC: Pressurised fluidised bed combustion

discriminating aspect. Completely different allocation factors may result depending on whether one individual decision-maker prescribes the allocation of expenses and emissions or whether several independent decision-makers need to agree on an allocation satisfactory for all the parties involved.

The fact that LCAs try to provide environmental information for purchase and investment decisions and the assumption that consumers pay attention to this information, should consequently lead to the application of more than mere economic allocation parameters. The task then becomes to allocate costs *and* environmental impacts to the jointly produced goods in order to achieve an enviro-economic performance comparable to or better than the one achieved by the competitors' products. Hence, whenever information about the environmental impacts of products in a particular product market is provided to and observed by the public, allocation parameters should consider these environmental aspects (besides economic and maybe other information).

It could be shown that system enlargement, the first step in the ISO 14041 procedure, is just a special case of an allocation factor when applying one-dimensional environmental indicators, such as environmental damage costs, Eco-indicator 95 or Eco-indicator 99 (GOEDKOOP & SPRIENSMA, 1999) results, to fully joint production processes. In this respect, the procedure stated in the ISO standard 14041 is questioned. It is suggested to move "system expansion" from step one to step three and to use "system expansion" in a way similar to the use of economic and other causalities.

Furthermore, it is suggested to more frequently consider the context in which joint product allocation has to be carried out (one individual versus several distinct decision-makers). The context highly influences both the procedure and the factors to be applied in joint product allocation, which in the end may substantially affect LCA results.

It has been shown that allocation in joint production is mainly performed for reasons of *competitiveness* and not for reasons of finding the economic or environmental "truth". That is why allocation in joint production entails inevitably value judgements that can have severe consequences for the outcome of an LCA and the conclusions drawn from it. One consequence of this realization is that joint product allocation should be carried out whenever possible by those responsible for the joint production process. Third parties, such as public authorities, should be involved in allocation negotiations only, where a major part of those which possibly make use of "jointly" produced products are yet unknown or not yet born. This is the case in long-term open-loop recycling issues (e.g., in the building sector), where a reuse or recycling in the far future of currently built-in materials is only speculative and highly uncertain.

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Appendix

The ISO 14041 procedure (Anonymous 1998):
On the basis of the principles mentioned before, the following stepwise procedure *) shall be applied:

1) Wherever possible allocation should be avoided by
   - dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these subprocesses,
   - expanding the product system to include the additional functions related to the co-products taking into account the requirements of 5.2.1.
2) Where allocation cannot be avoided, the system inputs and outputs should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them; i.e. they must reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. The resulting allocation will not necessarily be in proportion to any simple measure such as the mass or molar flows of co-products.
3) Where physical relationships alone cannot be established or used as the basis for allocation the inputs should be allocated between the products and functions in a way which reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

*): Step 1 does formally not belong to the allocation procedure.

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Modelling the Valuesphere and the Ecosphere:

Integrating the Decision Makers' Perspectives into LCA

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Abstract. Methods for Life Cycle Impact Assessment have to cope with two critical aspects, the uncertainty in values and the (unknown) system behaviour. LCA methodology should cope explicitly with these subjective elements. A structured aggregation procedure is proposed that differentiates between the technosphere and the ecosphere and embeds them in the valuesphere. LCA thus becomes a decision support system that models and combines these three spheres. We introduce three structurally identical types of LCA, each based on one coherent but different set of values. These sets of values can be derived from the Cultural Theory and are labeled as 'egalitarian', 'individualistic', and 'hierarchic'. Within Life Cycle Impact Assessment, a damage oriented assessment model is complemented with both a newly developed precautionary indicator designed to address unknown damage and an indicator for the manageability of environmental damages. The indicators for unknown damage and for manageability complete the set of indicators judged to be relevant by decision makers. The weights given to these indicators are also value-dependent. The framework proposed here answers the criticisms that present LCA methodology does not strictly enough separate subjective from objective elements and that it fails to accurately model environmental impacts.